The elastic dynamics analysis of band saw tightening system

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Abstract: In this paper, the node movement analysis of the levers of band saw tightening system is developed. A group of theoretical displacement and distortion equations of levers are presented using the Lagrange's equation. This could be the basis for the future research in the field of band saw's tightening system dynamics analysis.

Key word: Node distortion; Displacement function; Dynamics analysis.
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Structure and principle

The effect such as difference of diameter, rigidity, speed of feed, tartness of blade, and the disfigurement will bring the instantaneous change of saw blade length. If it was out of control, the flexuosity in the section surface of saw will arise, and even leads to the rupture of saw blade. In order to guarantee saw blade between two saw wheels working steadily, many kinds of tightening system are used, the upper saw wheel can rise or descend along with the length change of saw blade (Reynolds *et al.* 1996). Thereby, the tightening force of saw blade is held constantly.

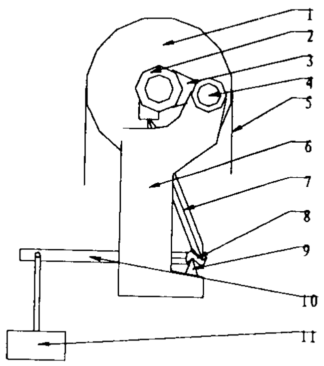

Fig. 1 Lever-weight tightening system sketch

1- upper saw wheel, 2--bearing shell, 3-- turning girder, 4-- eccentric shaft, 5--band saw blade, 6-- saw tappet, 7-- pole support, 8-- small turning shaft, 9--thimble, 10--lever, 11--weight.

Common band saw adopts multiplex lever-weight tightening system (see Fig. 1). The eccentric shaft supports the left border of the bearing shell. The eccentric shaft and the saw tappet are link together. The upper knife-edge of the pole support supports the right border of the bearing shell. The small turning shaft supports the lower knife-edge of the pole support. The thimble on the frame supports the knife-edge of the small turning shaft. The level lever is fixed on the middle of the pole support. The weight is hung at the end of the lever. Fig.2 shows the mechanics sketch of the multiplex lever-weight tightening system of common band saw.

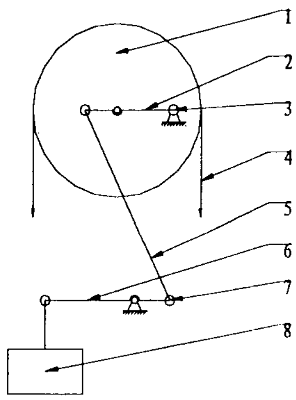

Fig. 2 Lever-weight tightening system mechanics sketch

1-upper saw wheel 2-turning girder 3-eccentric shaft 4-band saw blade 5-pole support 6-lever 7-small turning shaft 8-weight

Elastic dynamics analysis

We can think the tightening structure real movement as some levers pile up when we consider elasticity only.

1) Taking the tightening structure as rigid body (in Fig.3), when $\phi\ \dot{\phi}\ \ddot{\phi}$ are known, the four-lever struc-

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ture can be analyzed by common method.

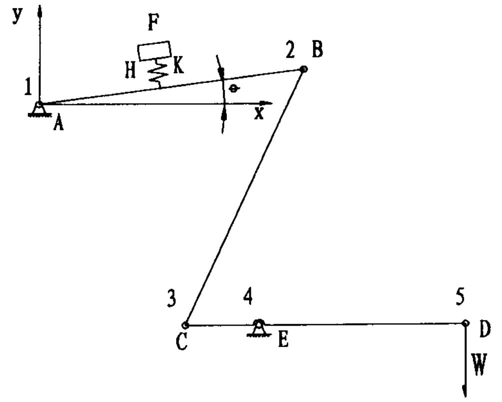

Fig. 3 Mechanics sketch of structure

When one main moving lever and frame combine to one structure, we analyze it all together at the moment. A FEM (Finite Element Method) analysis method of structural mechanics is applied for four-lever tightening elastic analysis in this thesis.

2) Fixing the structure on certain place(φ of one main moving lever), that is to fix one main moving lever with frame, turning the structure movement into fixed structure elastic movement with outer force (Huang *et al.* 1996).

We divide the structure into some units. The tinier it was divided, the more it approaches real situation, and the more difficult it becomes. We divide the band saw tightening system into four girder units, unit limits are called node, where exerting node force, forming node distortion. The whole elastic dynamics analysis of band saw tightening system is based on elastic dynamics analysis of girder units.

Node force, node distortion and unit displacement function

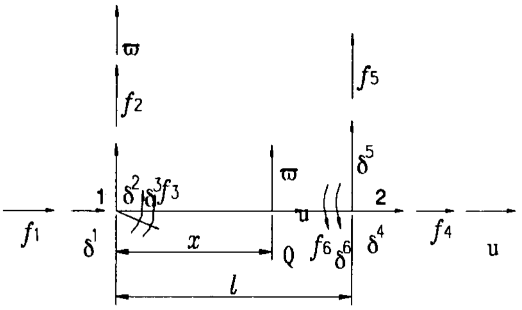

Fig. 4 Node force and node distortion of the girder units

Fig.4 is the girder unit concluded node 1 and 2. We take node 1 as origin, set up coordinate $u1\omega$, α is the inclination between $\vec{u}$ and coordinate $\vec{x}$. Node force: $\{f\}= [f_1, f_2, f_3, f_4, f_5, f_6]^T$, and node distortion: $\{\delta\}= [\delta_1, \delta_2, \delta_3, \delta_4, \delta_5, \delta_6]^T$. The distortion of any point Q in the unit, $\{e\} = [u, \omega]^T$, rested with $\{\delta\}$ and Q's position x, lengthways distortion u related to δ_1 and δ_4, crosswise distortion related ω to δ_2, δ_3, δ_5 and δ_6, therefore, u can be written as x once expression, ω can be written as x thrice expression, we can get the relation between $\{e\}$ and $\{\delta\}$ using the undetermined coefficient method:

$$u=\delta_1+(\delta_4-\delta_1)x/l=(1-x/l)\delta_1+(x/l)\delta_4$$

$$\omega=(1-3x^2/l^2+2x^3/l^3)\delta_2+(x-2x^2/l^2+x^3/l^3)\delta_3+(3x^2/l^2-2x^3/l^3)\delta_5+(-x^2/l^2+x^3/l^3)\delta_6 \quad (1)$$

Where, l is the girder length in Eq.1. We mark $u = N_{11}\delta_1 + N_{14}\delta_4$ and $\omega = N_{22}\delta_2 + N_{23}\delta_3 + N_{25}\delta_5 + N_{26}\delta_6$.

Express as matrix,

$$\{e(x)\} = \begin{Bmatrix} u \\ \omega \end{Bmatrix} = \begin{bmatrix} N_{11} & N_{14} & 0 & 0 & 0 & 0 \\ 0 & 0 & N_{22} & N_{23} & N_{25} & N_{26} \end{bmatrix} \times \begin{bmatrix} \delta_1 \\ \delta_4 \\ \delta_2 \\ \delta_3 \\ \delta_5 \\ \delta_6 \end{bmatrix}$$

and matrix,

$$N = \begin{bmatrix} N_{11} & N_{14} & 0 & 0 & 0 & 0 \\ 0 & 0 & N_{22} & N_{23} & N_{25} & N_{26} \end{bmatrix}$$

We call u and ω in Eq.1 as the unit replacement function included x. We can derive any distortion in unit when $\{\delta\}$ is known.

We set up whole system equation using the Lagrange's equation.

$$\frac{d}{dt}\left(\frac{\partial E}{\partial \dot{\delta}_i}\right) - \frac{\partial E}{\partial \delta_i} + \frac{\partial U}{\partial \delta_i} = F_i \quad (2)$$

where, E is each unit kinetic energy, U is each unit potential energy, and F_i is each unit's generalized force.

Kinetic energy *E* and equivalent quality matrix

We suppose that girder unit's section is equality, unit kinetic energy is E (ρ is the quality per unit length),

$$E=\frac{\rho}{2}\left\{\begin{array}{l}\int (N_{11}\dot{\delta}_1+N_{22}\dot{\delta}_4)^2\,dx + \\ \int_0^L (N_{22}\dot{\delta}_2+N_{23}\dot{\delta}_3+N_{25}\dot{\delta}_5+N_{26}\dot{\delta}_6)^2\,dx\end{array}\right\}$$

$$\frac{\mathrm{d}}{\mathrm{d}_i}(\frac{\partial E}{\partial \dot{\delta}_i}) - \frac{\partial E}{\partial \delta_i} = \sum_{j=1}^{6} m_{ij} \ddot{\delta}_j$$

where, i =1, 2, ⋯6, m_{ij} is the girder unit 's equivalent quality;

at i =1, 4 and j =1,4 , $m_{ij} = \rho\int_0^l N_{1i} n_{1j} \mathrm{d}x$;

at i =1,4 and j =2,3,5,6 , m_{ij}=0;

at i =2,3,5,6 and j =2,3,5,6, $m_{ij} = \rho\int_{0.}^l nN_{2i} N_{2j} \mathrm{d}x$;

at i =2.3.5.6 and j=1,4, m_{ij}=0.

Obviously, $m_{ij}= m_{ji}$. The followed could be derive,

$$\begin{Bmatrix} \frac{\mathrm{d}}{\mathrm{d}_1}(\frac{\partial E}{\partial \dot{\delta}_1}) - \frac{\partial E}{\partial \delta_1} \\ \frac{\mathrm{d}}{\mathrm{d}_2}(\frac{\partial E}{\partial \dot{\delta}_2}) - \frac{\partial E}{\partial \delta_2} \\ \vdots \\ \frac{\mathrm{d}}{\mathrm{d}_6}(\frac{\partial E}{\partial \dot{\delta}_6}) - \frac{\partial E}{\partial \delta_6} \end{Bmatrix} = \begin{Bmatrix} m_{11} & 0 & 0 & m_{14} & 0 & 0 \\ 0 & m_{22} & m_{23} & 0 & m_{25} & m_{26} \\ 0 & m_{32} & m_{33} & 0 & m_{35} & m_{36} \\ m_{41} & 0 & 0 & 0 & 0 & 0 \\ 0 & m_{52} & m_{53} & 0 & m_{55} & m_{56} \\ 0 & m_{62} & m_{63} & 0 & m_{65} & m_{66} \end{Bmatrix} \begin{bmatrix} \ddot{\delta}_1 \\ \ddot{\delta}_2 \\ \ddot{\delta}_3 \\ \ddot{\delta}_4 \\ \ddot{\delta}_5 \\ \ddot{\delta}_6 \end{bmatrix} = [m][\ddot{\delta}]$$

where, [m] is called equivalent quality matrix. We bring N_{11}, N_{14}, N_{22}, N_{23}, N_{24}, N_{26} into m_{ij}, and integrate it.

$$[m] = \begin{bmatrix} 140 & 0 & 0 & 70 & 0 & 0 \\ 0 & 156 & 22l & 0 & 54 & -13l \\ 0 & 22l & 4l^2 & 0 & 13l & -3l^2 \\ 70 & 0 & 0 & 140 & 0 & 0 \\ 0 & 54 & 13l & 0 & 156 & -22l \\ 0 & -13l & -3l^2 & 0 & -22l & 4l^2 \end{bmatrix} \qquad (3)$$

Potential energy U and unit rigidity matrix

Suppose that unit area is A, material elastic modulus is E, except calculating lengthways distortion caused by bending.

$$U_1 = \frac{1}{2}\int_0^l EA(\frac{\partial U}{\partial x})^2 \mathrm{d}x = \frac{1}{2}EA\int_0^l (N'_{11}\delta_1 + N'_{14}\delta_4)^2 \mathrm{d}x$$

Where, N_{11} is each girder unit character coefficient.

$$N'_{11} = \frac{\mathrm{d}N_{11}}{\mathrm{d}x} \qquad N'_{14} = \frac{\mathrm{d}N_{14}}{\mathrm{d}x}$$

suppose girder unit-section inertia moment is I, and it is constant. Ignore the effect of cut distortion. Girder inertia stain energy is:

$$U_2 = \frac{EI}{2}\int_0^l w''^2 \mathrm{d}x =$$

$$\frac{EI}{2}\int (N''_{22}\delta_2 + N''_{23}\delta_3 + N''_{25}\delta_5 + N''_{26}\delta_6)^2 \mathrm{d}x$$

where

$$N''_{22} = \frac{\mathrm{d}^2 N_{22}}{\mathrm{d}x^2}, \qquad N''_{23} = \frac{\mathrm{d}^2 N_{23}}{\mathrm{d}x^2}$$

$$N''_{25} = \frac{\mathrm{d}^2 N_{25}}{\mathrm{d}x^2}, \qquad N''_{26} = \frac{\mathrm{d}^2 N_{26}}{\mathrm{d}x^2}$$

Therefore, the general potential energy $U = U_1 + U_2$.

$$\frac{\partial u}{\partial \delta_i} = \sum k_{ij}\delta_j \qquad i = 1,2,\cdots,6$$

for i =1, 4,

$$k_{ij} = EA\int_0^l N'_{1j} N'_{1i} \mathrm{d}x \qquad j = 1,4$$

for i =2,3,5,6,

$$k_{ij} = EI\int_0^l N''_{2i} N''_{2j} \mathrm{d}x \qquad j = 2,3,5,6$$

$$k_{ij} = 0$$

change into matrix,

$$\left\{\frac{\partial U}{\partial \delta}\right\} = [k]\{\delta\}$$

where,

$$\left\{\frac{\partial U}{\partial \delta}\right\} = [\frac{\partial U}{\partial \delta_1}, \frac{\partial U}{\partial \delta_2}, \cdots, \frac{\partial U}{\partial \delta_6}]^T$$

$$\{\delta\} = [\delta_1, \delta_2, \cdots, \delta_6]^T$$

$$[k] = \begin{bmatrix} k_{11} & 0 & 0 & k_{14} & 0 & 0 \\ 0 & k_{22} & & 0 & k_{25} & k_{26} \\ 0 & & k_{33} & 0 & k_{35} & k_{36} \\ k_{41} & 0 & 0 & k_{44} & 0 & 0 \\ 0 & k_{52} & k_{53} & 0 & k_{55} & k_{56} \\ 0 & k_{62} & k_{63} & 0 & k_{65} & k_{66} \end{bmatrix} \qquad (4)$$

Eq. 4 is called unit rigidity matrix, k_{ij}=k_{ji} (symmetrical matrix too). Take N'_{11}、N'_{14}、N''_{22}、N''_{23}、N''_{25}、N''_{26} expression into Eq.4 and integrate it.

$$[k] = \begin{bmatrix} EA/l & 0 & 0 & -EA/l & 0 & 0 \\ 0 & 12EI/l^3 & 6EI/l^2 & 0 & -12EI/l^3 & 6EI/l^2 \\ 0 & 6EI/l^3 & 4EI/l & 0 & -6EI/l^2 & 2EI/l \\ -EA/l & 0 & 0 & EA/l & 0 & 0 \\ 0 & -12EI/l^2 & -6EI/l^2 & 0 & 12EI/l^3 & -6EI/l^2 \\ 0 & 6EI/l & 2EI/l & 0 & -6EI/l^2 & 4EI/l \end{bmatrix} \qquad (5)$$

Confirmation of the generalized force

The right side of the Lagrange's equation is generalized force, if there is node force exerting at the unit only, $F_i = f_i$; if there are other forces (including rigidity inertia force), the generalized force,

$F_i = F^{(0)}_i + f_i$.

where, f_i is node force, $F_i^{(0)}$ is equivalent force except node force.

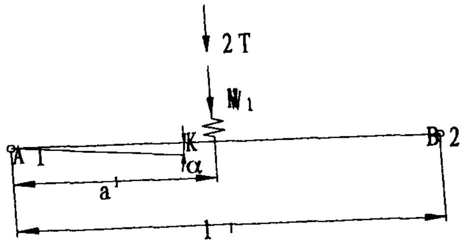

Fig. 5 The force sketch on girder AB

Fig.5 presents the force exerting at girder AB (node 1, 2). Where, F is the force exerted at AB of bearing, and it is $F = 2T + W_1 + Ka_1 \cdot \alpha$, where, T is the tightening force of saw blade, W_1 is the weight of the upper saw wheel, a_1 is the distance between exerting point and A (join point), α is the inclination, K is the rigidity of the shaft of the saw wheel (ladder shaft). The figure of shaft of the saw wheel is shown in Fig.6

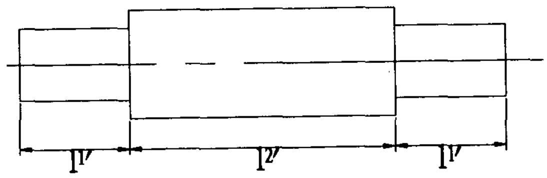

Fig. 6 The figure of shaft of the saw wheel

Therefore,

$$K = \frac{K_1 K_2}{K_1 + 2K_2}$$

K_1 is the rigidity of thin portion, $K_1 = \frac{G_1 I_1}{l_1'}$

l_1' is the length of thin portion;

K_2 is the rigidity of thick portion, $K_2 = \frac{G_2 I_2}{l_2'}$

l_2' is the length of thick portion;

Then the generalized force,

$$F_1^{(0)} = 0; \quad F_2^{(0)} = \frac{F(l_1 - a_1)^2}{l^2}(1 + \frac{2a_1}{l_1}); \tag{6}$$

$$F_3^{(0)} = \frac{F(l_1 - a_1)^2}{l_1^2} a_1$$

Girder BC (node 2, 3) (Fig.7),

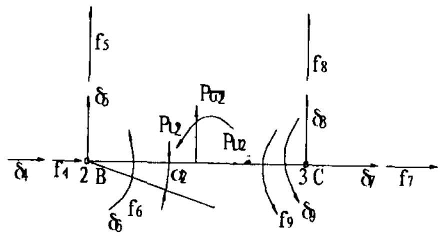

Fig. 7 The force sketch of girder BC

$$F_i^{(0)} = f_i$$

Girder CE (node 3, 4) (Fig.8),

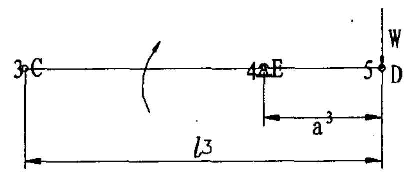

Fig. 8 The force sketch of girder CE

W is the force exerting point,

$$F_1^{(0)} = 0; \; F_2^{(0)} = -6Wa_3^2 \frac{(l_3 - a_3)}{l_3};$$

$$F_3^{(0)} = Wa_3^2 \frac{[a_3 - 2(l_3 - a_3)]}{l_3^2}; \; F_4^{(0)} = 0 \tag{8}$$

Girder ED,

$$F_1^{(0)} = 0; \; F_2^{(0)} = \frac{Wa_3}{l_3}; \; F_3^{(0)} = 0; \; F_4^{(0)} = 0 \tag{9}$$

Unit equation

Each unit equation of tightening system is,

$$[m]\{\ddot{\delta}\} + [k]\{\delta\} = \{F\} = \{f\} + \{F^{(0)}\} \tag{10}$$

dividing the tightening system into four-lever unit, the symbols of node and node distortion present in Fig.9-12.

Girder AB (Fig.9),

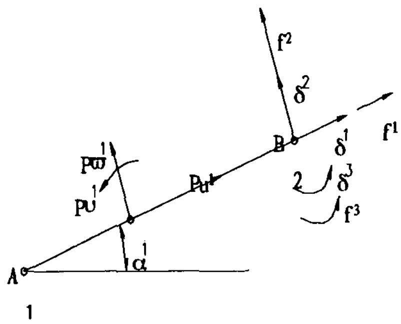

Fig. 9 The force sketch of girder AB

Girder BC (Fig.10),

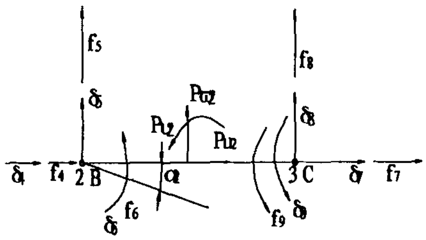

Fig. 10 The force sketch of girder BC

Girder CE (Fig.11),

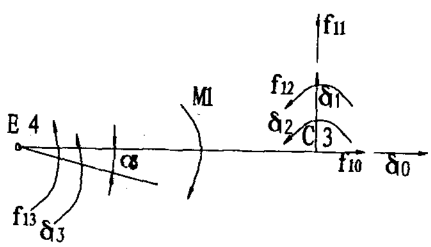

Fig. 11 The force sketch of girder CE

Girder ED (Fig.12),

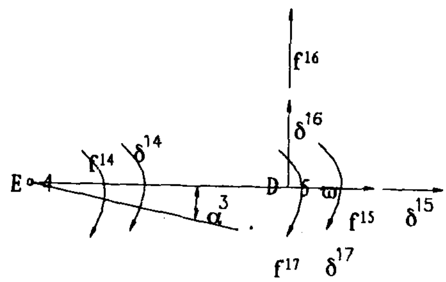

Fig. 12 The force sketch of girder ED

Girder AB joins frame at A, just as cantilever, without node distortion, degree of freedom is 3. $\delta_1 = \delta_2 = \delta_3 = 0$ in Fig.4. The quality and rigidity matrixes are,

$$[m_1] = \frac{m_1}{420}\begin{bmatrix} 140 & 0 & 0 \\ 0 & 156 & -22l_1 \\ 0 & -22l_1 & 4l_1^2 \end{bmatrix}$$

$$[k]_1 = \begin{bmatrix} EA/l & 0 & 0 \\ 0 & 12EI/l^3 & 6EI/l^2 \\ 0 & 6EI/l^2 & 4EI/l^2 \end{bmatrix}$$

$$[\delta]_1 = \{\delta_1, \delta_2, \delta_3\}^T \qquad \{F_1\} = [F_1, F_2, F_3]^T$$

For girder CE, only E can running, the degree of freedom is 4.

$$[m]_3 = \frac{m_3}{420}\begin{bmatrix} 4(l_3-a_3)^2 & 0 & 13(l_3-a_3) & -3(l_3-a_3)^2 \\ 0 & 140 & 0 & 0 \\ 13(l_3-a_3) & 0 & 156 & -22(l_3-a_3) \\ -3(l_3-a_3)^2 & 0 & -22(l_3-a_3) & 4l_3^2 \end{bmatrix} \quad (11)$$

where, m_3 is the quality of girder CE.

$$[k]_3 = \begin{bmatrix} \frac{4EI}{l_3-a_3} & 0 & \frac{-6EI}{(l_3-a_3)^2} & \frac{2EI}{l_3-a_3} \\ 0 & \frac{EA}{l_3-a_3} & 0 & 0 \\ \frac{-6EI}{(l_3-a_3)^2} & 0 & \frac{12EI}{(l_3-a_3)^2} & \frac{-6EI}{(l_3-a_3)^2} \\ \frac{2EI}{l_3} & 0 & \frac{6EI}{l_3-a_3} & \frac{4EI}{l_3-a_3} \end{bmatrix} \quad (12)$$

Girder DE, only E can turn, the degree of freedom is 4, therefore,

$$[m]_4 = \frac{m_4}{420}\begin{bmatrix} 4a_3^2 & 0 & 13a_3 & -3l_3^2 \\ 0 & 140 & 0 & 0 \\ 13a_3^2 & 0 & 156 & -22l_3 \\ -3a_3^2 & 0 & -22a_3 & 4l_3 \end{bmatrix} \quad (13)$$

where, m_4 is the quality of girder DE (kg); E is the elastic modulus of girder DE (GPa); l_3 is the length of girder DE (m).

$$[k]_4 = \begin{bmatrix} \frac{4EI}{a_3} & 0 & \frac{-6EI}{a_3^2} & \frac{2EI}{l_3} \\ 0 & \frac{EI}{a_3} & 0 & 0 \\ \frac{-6EI}{a_3^2} & 0 & \frac{12Ei}{a_3^2} & \frac{-6EI}{a_3} \end{bmatrix} \quad (14)$$

$$\{\delta\}_4 = \{\delta_{14}\ \delta_{15}\ \delta_{16}\ \delta_{17}\}^T \quad (15)$$

$$\{F\}_4 = \{F_{14}\ F_{15}\ F_{16}\ F_{17}\}^T \quad (16)$$

The degree of freedom is 6. Therefore, we can change the corresponding symbols of $[m]$ and $[k]$.

$$\{\delta\}_2 = \{\delta_4\ \delta_5\ \delta_6\ \delta_7\ \delta_8\ \delta_9\}^T \quad (17)$$

$$[F]_2 = [f_4\ f_5\ f_6\ f_7\ f_8\ f_9]^T \quad (18)$$

The generalized force is:
Girder AB,
The force F exerts at O, therefore,

$$\{F\}_1=\begin{bmatrix} f_1 & \dfrac{F(l_1-a_1)^2}{l_1^2}\left(1+\dfrac{2a_1}{l_1}\right)+f_2 & \dfrac{F\left(l_1^0-a_1\right)^2}{l_1}+f_3 \end{bmatrix}^T \qquad (19)$$

Girder BC,

$$\{F\}_2=\{F_4\ \ F_5\ \ F_6\ \ F_7\ \ F_8\ \ F_9\}^T \qquad (20)$$

Girder CE,

$$[F]_3=\begin{bmatrix} f_{10} & -6wa_3\dfrac{[a_3-2(l_3-a_3)]}{l_3^2}+f_{11}+\dfrac{wa_3^2[a_3-2(l_3-a_3)]}{l_3^2}+f_{12} & f_{13} \end{bmatrix}^T \qquad (21)$$

Girder ED,

$$[F]_4=\begin{bmatrix} f_{13} & f_{14}+\dfrac{wa_3^2}{l_3}-f_{15} & f_{16} \end{bmatrix}^T \qquad (22)$$

Therefore, we can get the follow,
the unit equations are,

$$\left.\begin{aligned} [m]_1\{\ddot{\delta}\}_1+[k]_1\{\delta\}_1&=\{F\}_1\\ [m]_2\{\ddot{\delta}\}_2+[k]_2\{\delta\}_2&=\{F\}_2\\ [m]_3\{\ddot{\delta}\}_3+[k]_3\{\delta\}_3&=\{F\}_3\\ [m]_4\{\ddot{\delta}\}_4+[k]_4\{\delta\}_4&=\{F\}_4 \end{aligned}\right\} \qquad (23)$$

System equation

In Eq.4, translate the first row into the fourth row for $[m]_4[k]_4\{\delta\}_4\{F\}_4$ of pole DE. That is to say,

$$\{\delta\}_4=\{\delta_{13}\ \ \delta_{14}\ \ \delta_{15}\ \ \delta_{16}\} \qquad (24)$$

Then combine it orderly as follow:

$$\begin{bmatrix} [m]_1 & & & \\ & [m]_2 & & \\ & & [m]_3 & \\ & & & [m]_4 \end{bmatrix}\begin{Bmatrix} \{\ddot{\delta}\}_1\\ \{\ddot{\delta}\}_2\\ \{\ddot{\delta}\}_3\\ \{\ddot{\delta}\}_4 \end{Bmatrix}+ \begin{bmatrix} [k]_1 & & & \\ & [k]_2 & & \\ & & [k]_3 & \\ & & & [k]_4 \end{bmatrix}\begin{Bmatrix} \{\delta\}_1\\ \{\delta\}_2\\ \{\delta\}_3\\ \{\delta\}_4 \end{Bmatrix}=\begin{Bmatrix} \{F\}_1\\ \{F\}_2\\ \{F\}_3\\ \{F\}_4 \end{Bmatrix} \qquad (25)$$

for short,

$$[\tilde{m}]\{\ddot{\delta}\}+[\tilde{k}]\{\delta\}=\{F\} \qquad (26)$$

$$[\tilde{m}]=\begin{bmatrix} [m]_1 & & & \\ & [m]_2 & & \\ & & [m]_3 & \\ & & & [m]_4 \end{bmatrix}$$

$$\{\ddot{\delta}\}=\begin{Bmatrix} \{\ddot{\delta}\}_1\\ \{\ddot{\delta}\}_2\\ \{\ddot{\delta}\}_3\\ \{\ddot{\delta}\}_4 \end{Bmatrix} \qquad [\tilde{k}]=\begin{bmatrix} [k]_1 & & & \\ & [k]_2 & & \\ & & [k]_3 & \\ & & & [k]_4 \end{bmatrix}$$

$$\{\delta\}=\begin{Bmatrix} \{\delta\}_1\\ \{\delta\}_2\\ \{\delta\}_3\\ \{\delta\}_4 \end{Bmatrix} \qquad \{F\}=\begin{Bmatrix} \{F\}_1\\ \{F\}_2\\ \{F\}_3\\ \{F\}_4 \end{Bmatrix}$$

Conclusion

We can get the point distortion $\{\delta\}$ of any girder at any moment from the solution of Eq.26.

We can adjust the weight and appearance size of girder to decrease the distortion at any moment to the full, and increase the stability and the veracity of the system.

The relation analysis of the quality matrix and the rigidity matrix in Eq.26 could be the basis for the future research of tightening system dynamics character analysis of band saw.

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